

The LXeGRIT Compton Telescope Prototype: Current Status and Future Prospects

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ABSTRACT

LXeGRIT is the first prototype of a novel concept of Compton telescope, based on the complete 3-dimensional reconstruction of the sequence of interactions of individual γ -rays in one position sensitive detector. This balloon-borne telescope consists of an unshielded time projection chamber with an active volume of $400 \text{ cm}^2 \times 7 \text{ cm}$ filled with high purity liquid xenon. Four VUV PMTs detect the fast xenon scintillation light signal, providing the event trigger. 124 wires and 4 anodes detect the ionization signals, providing the event spatial coordinates and total energy. In the period 1999 – 2001, LXeGRIT has been extensively tested both in the laboratory and at balloon altitude, and its response in the MeV region has been thoroughly characterized. Here we summarize some of the results on pre-flight calibration, event reconstruction techniques, and performance during a 27 hour balloon flight on October 4 – 5. We further present briefly the on-going efforts directed to improve the performance of this prototype towards the requirements for a base module of a next-generation Compton telescope.

Keywords: gamma-rays, instrumentation, imaging, telescope, balloon missions, high energy astrophysics

1. THE TPC APPROACH TO A COMPTON TELESCOPE

Between the energy regimes of photoabsorption and pair production, about 250 keV and 6 MeV in xenon, γ -rays interact in matter predominantly via the Compton process. A Compton telescope is thus the most promising approach to measure efficiently the distribution of cosmic sources emitting in the MeV energy band. In a double scatter telescope such as COMPTEL,[?] the restriction on the event topology to two interactions recorded in two separate detector planes, results in a relatively low detection efficiency ($\ll 1\%$). This figure is greatly improved in a homogeneous, self-triggered, three-dimensional (3D) position sensitive detector such as a liquid xenon time projection chamber (LXeTPC), as proposed by Aprile et al..[?] In a TPC of large sensitive volume, passive materials are minimized and a variety of different event topologies are used for imaging, substantially increasing detection efficiency. With the 3D position sensitivity, single-site events are easily identified and rejected as background, as they are not useful for imaging. Multiple-site events are associated with MeV γ -rays from both source and background. As for any Compton telescope, the imaging capability greatly enhances signal over background compared to formerly employed simple photon counters. In addition, the wealth of information recorded allows for more sophisticated event selections based on Compton kinematics, interaction locations, or interaction separation.

In absence of a time-of-flight measurement, the correct order of the multiple interactions has to be determined from the redundant kinematical and geometrical information measured for each event. The efficiency of this sequence reconstruction is directly determined by the accuracy of the energy and position measurements. As previously shown in Aprile et al..[?] and more recently by other groups^{?,?,?}, event reconstruction based on Compton kinematics allows to correctly order the

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interactions and to discriminate against background, e.g., from non-Compton sequences or multiple coincident gamma-rays.

The LXeGRIT is the outcome of a systematic program initiated at Columbia University with NASA support to develop the LXeTPC technology for MeV astrophysics. Experiments with LXe detectors were carried out to measure charge and light yields, energy and position resolution, electron drift velocity and mobility, etc.[?] Following these basic studies, a LXeTPC, with a sensitive volume of 2800 cm³, was developed and its performance established with a varied of γ -ray sources. The same TPC is used for the balloon-borne LXeGRIT instrument.

The detector works as follows. Both ionization and scintillation signals are detected to measure the event spatial coordinates and the energy. The fast UV (175 nm) Xe light is detected by four PMTs viewing the sensitive volume from below, through quartz windows. The OR of the PMT signals is the TPC trigger signal, marking time zero of each event. The charge signals induced by free electrons drifting under the applied electric field are detected on two orthogonal planes of parallel wires, providing X-Y position information with millimeter accuracy. The wires pitch is 3 mm, and the separation between X and Y planes is also 3 mm. Below the wires, at a distance of 3 mm, four anodes are used to collect the total charge liberated in the event. The charge is directly proportional to energy. The 62 X-wires and 62 Y-wires and the anode are amplified and digitized at 5 MHz, with 8 bit precision for the wires and 10 bit precision for the anodes. The digitized data are stored with 256 samples per event, covering more than the maximum drift time of 35 μ s. The absolute drift time measurement gives the event depth of interaction (Z-position), with an accuracy of 300 μ m. This charge readout was designed and tested to image the point-like ionization clouds (< 1mm) produced by low energy Compton electrons and photoelectrons which are typical of MeV γ -ray interactions in the dense LXe. The signal size associated with these clouds is very small (W=15.6 eV compared to W=2.96 eV for Ge and W=3.62 eV in Si). A key prerequisite for this detector to work is to minimize the signal loss due to electron trapping by impurities in the liquid. In LXeGRIT free electrons are drifted over the TPC maximum distance of 7 cm with very little attenuation, and the remaining 5% maximum charge loss for full drift length is corrected for based on the known Z-position.

The TPC is enclosed in a cylindrical vessel filled with 7 liters of pure LXe kept at $\sim -95^\circ\text{C}$ by a controlled flow of LN₂ through a condenser. The vessel is thermally insulated with a vacuum cryostat. The lower section of the cryostat houses the four PMTs of the xenon light readout, as well as the HV distribution circuitry for the wires and the cathode.

2. THE LXEGRIT BALLOON FLIGHT PROGRAM

To demonstrate the operation and performance of the LXeTPC with γ -rays in the near space environment, the detector was turned into a balloon payload called LXeGRIT. This instrument is the first prototype of a Compton telescope using a single, 3D position sensitive detector like a LXeTPC. Having shown its γ -ray imaging capability in the controlled environment of the laboratory, it was clear that the practical implementation of this new type of instrument for astrophysics would present a number of challenges which needed to be directly tested with a balloon flight. For this purpose, all detector subsystems had to be capable of sustaining the near vacuum conditions and the temperature extremes encountered during a balloon flight. In addition, two major new developments were required to make a balloon experiment with the LXeTPC: a low-power readout electronics and data acquisition flight system, and an instrumentation and control system. These systems were developed in close collaboration and with engineering support from Marshall Space Flight Center and are described in Aprile et al.[?] The front-end electronics, also described in,[?] was developed in collaboration with the Waseda group in Japan and the Clear Pulse Company. The hardware modifications to the original systems, and the new data acquisition software which followed the 1997 flights, are discussed in Aprile et al.[?] A parallel effort involved extensive modifications of an existing gondola and veto shield systems provided by the University of New Hampshire. Being a Compton telescope, LXeGRIT does not require an active pointing system. The instrument's zenith direction and azimuth orientation is provided by a sensor combining 3-axis magnetometer and 3-axis accelerometer. This information, together with the knowledge of the payload geographical coordinates, is needed for imaging analysis of celestial sources. The flight data are stored in two 36-G-byte disk drives and also sent via telemetry at 2×500 kbps to the ground station. Table 1 summarizes the instrument characteristics.

2.1. Pre-flight Calibration

Results from the 1999 pre-flight calibration have been reported in Aprile et al.[?] The 2000 pre-flight calibration gives a similar spectral and spatial resolution performance, but differs in trigger efficiency and data acquisition (DAQ) speed. The

Energy Range	0.15 – 10 MeV
Energy Resolution ($FWHM$)	$8.8\% \times (1 \text{ MeV}/E)^{1/2}$
Position Resolution (1σ)	1 mm (3 dimensions)
Angular Resolution (1σ)	3.8° at 1.8 MeV
Field of View ($FWHM$)	1 sr
Detector Active Volume	20 cm \times 20 cm \times 7 cm
Instrument Mass, Power	2000 lbs, 450 W
Telemetry, On-board Data Storage	2×500 kbps, 2×36 GB

Table 1. LXeGRIT characteristics in the balloon flight 2000 configuration.

electronic gain on the anode signal was increased by a factor of ~ 2 (see Fig. 1), reducing the maximum energy before saturation of the FADC dynamical range from ~ 20 MeV in 1999 to ~ 10 MeV in 2000, which is a more appropriate upper limit for this experiment.

The intrinsic energy resolution at a drift field of 1 kV/cm is consistent with $\Delta E_{\text{LXe}}/E = 8.8\% \sqrt{1 \text{ MeV}/E}$ (FWHM) and it is linear for γ -rays in the energy range 0.5-4.4 MeV (see Fig. 2), in accordance with results from small ionization chambers. The contribution from electronic noise is about 55 keV (FWHM).

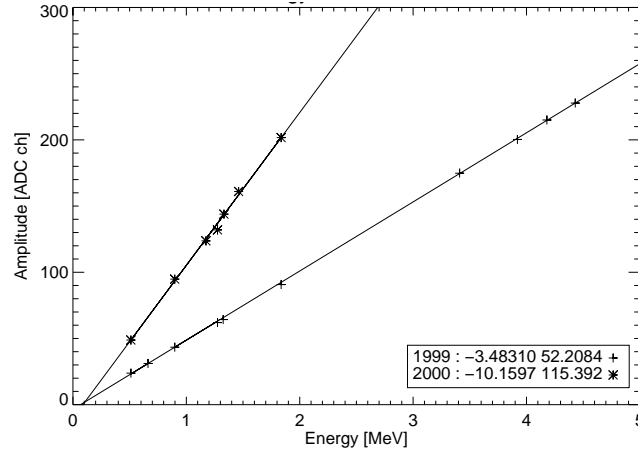


Figure 1. LXeGRIT energy calibration curve for one of the four anodes from '99 (*crosses*) and 2000 (*stars*) pre-flight calibration data.

The large amount of information made available for each γ -ray event by the fine granularity of the TPC allows a detailed spectral analysis. The precise knowledge of the event topology suggests a separate analysis for events with different interaction multiplicity. Also due to the relatively large size of the LXeTPC, for γ -ray energies larger than ~ 800 keV, the detection efficiency is significantly higher for multiple-site events than for single-site events. Summing up the separate interactions of multiple-site events, a largely enhanced *peak-to-Compton* ratio is also obtained, as shown in Fig. 3 for an ^{88}Y (898 and 1836 keV lines) and a ^{22}Na source (511 and 1275 keV).

The Compton Sequence Reconstruction (CSR) is based on the testing of Compton kinematics, using the redundant information available in the measurement of positions and energy depositions in three or more interactions. We currently employ a test statistic which measures the differences square of the cosines of the geometrically measured angles ϕ_{geo} and the photon scattering angles $\bar{\phi}$ inferred from the measured energy depositions. This sum is weighted by the measurement uncertainties in both quantities, $\sigma_{\cos \bar{\phi}}$ and $\sigma_{\cos \phi_{\text{geo}}}$:

$$T = \frac{1}{N-2} \sum_{i=2}^{N-1} \frac{(\cos \bar{\phi}_i - \cos \phi_{\text{geo}, i})^2}{\sigma_{\cos \bar{\phi}, i}^2 + \sigma_{\cos \phi_{\text{geo}, i}}^2} \quad (1)$$

where N is the number of interactions in the detector. Ideally, the test statistic would be zero for the correct sequence if the photon is fully contained. With measurement errors and a contribution from Doppler broadening, resulting from the

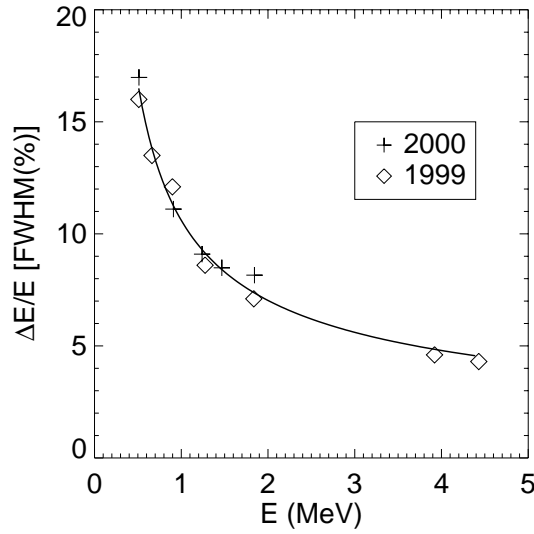


Figure 2. LXeGRIT energy resolution vs. energy, at 1 kV/cm, as measured from '99 (*open diamonds*) and 2000 (*crosses*) pre-flight calibration data.

binding energy of the interacting electron, T is larger than zero. Even so, the correct interaction sequence most likely produces the minimum value of the test statistic among all possible sequences. In addition to minimizing T , an upper threshold on T can help in discriminating against photons that are not fully absorbed or that interact through mechanisms other than Compton scattering. Details can be found in Oberlack et al.[?]

The CSR algorithm has been applied to multiple-site events from ^{22}Na , ^{60}Co and ^{88}Y sources placed a few meters above the LXeTPC. Event selections made possible by 3D position resolution and CSR result in a dramatic suppression of background, as shown in the clean energy spectrum of ^{88}Y obtained with 3-site Compton events (Fig. 4). For photons losing energy in two interactions only, the problem as in Eq. 1 is underconstrained, but probabilistic approaches can still be used, which turned out quite effective especially for γ -ray energies above 1 MeV.

Once the correct interaction sequence has been found we can image γ -ray sources. Imaging proceeds as for a classical double scatter Compton telescope, i.e. by determination of the scatter direction between first and second interaction and by the measurement of the Compton scatter angle ϕ , based on measured energy deposits and Compton kinematics. The measured scatter angle define a circle on the sky, on which the γ -ray source is located. Many photons from the same source result in intersecting “event circles” with varying radii. The intersection point defines the source position. Additional information is available from the known probability density for scatter angles within the telescope for a given source location. This leads to more powerful imaging techniques based on likelihood analysis. Given the necessary event-by-event analysis, it is efficient to employ so called list-mode imaging techniques,[?] where the probability for a photon to originate in a certain point in the sky is determined for each event, rather than in a binned dataspace as used by COMPTEL. We have implemented imaging software and tested the method successfully on calibration data. An in-depth discussion of these results will be reported elsewhere.

The angular resolution of a Compton telescope is given by the “angular resolution measure” $ARM = \bar{\phi} - \phi_{\text{geo}}$. Fig. 5 shows the measured ARM distribution at 1.8 MeV, consistent with the expectation (see Fig. 6 for comparison). Clearly, events with smaller scatter angle would result in better angular resolution.

The detection efficiency for Compton events has been both directly measured and studied through Monte Carlo simulations taking into account the LXeGRIT mass model, minimum energy threshold and energy and spatial resolution. It varies between 1.5 % and 4 % depending on energy and event selection, which corresponds to a quite large effective area for this kind of detector, from 6 to 16 cm^2 . This efficiency does not account for the limited DAQ speed (see Aprile et al.[?]) and inefficiencies of the light-trigger, which in the end dominate the total efficiency.

As discussed in Oberlack et al.[?], for the 2000 flight we chose to *reduce* the trigger efficiency to specifically select multiple Compton events in the few MeV region and to be less sensitive to lower-energy gamma-rays, given the dead-time

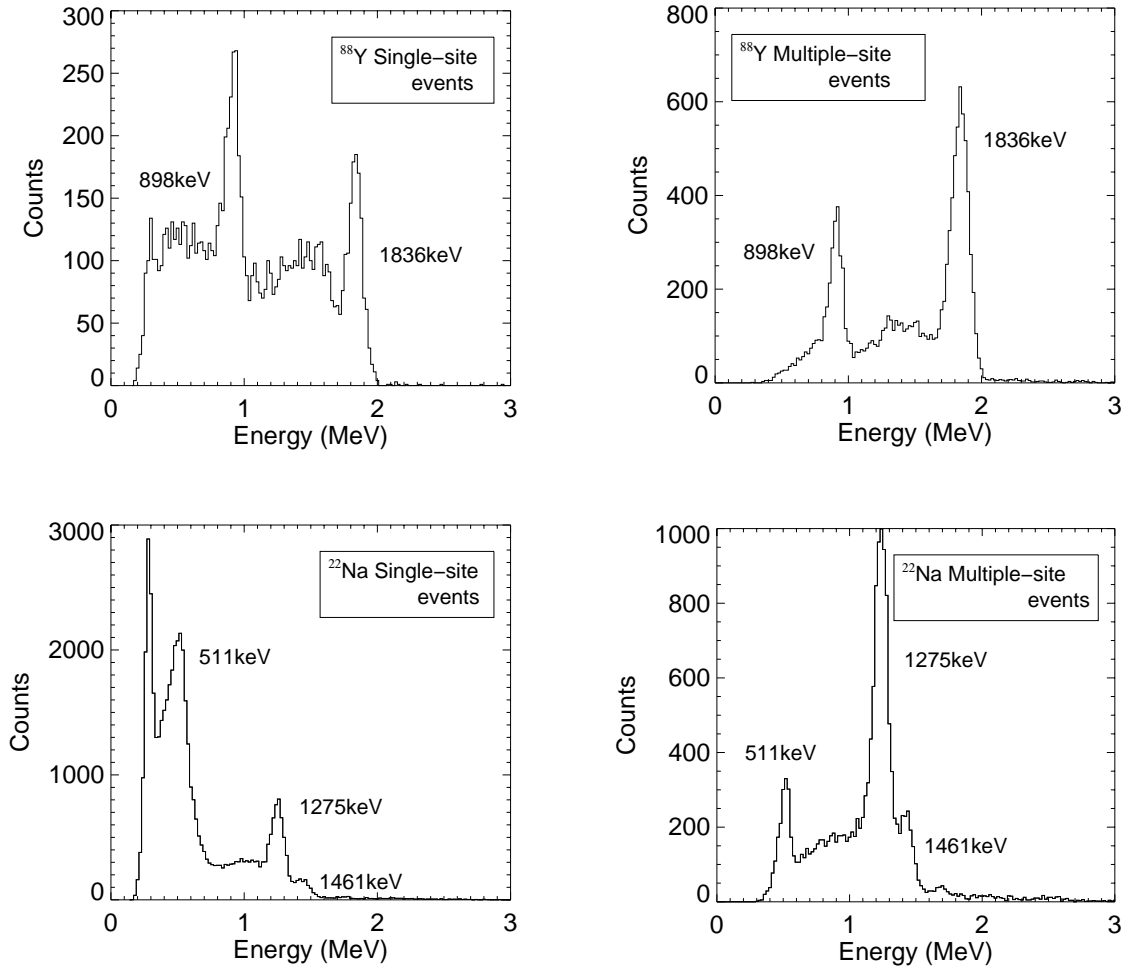


Figure 3. *Top left:* energy spectrum for single-site events from an ^{88}Y source (898 and 1836 keV lines). *Top right:* multiple-site events, ^{88}Y , same experiment. *Bottom left:* energy spectrum for single-site events from a ^{22}Na source (511 and 1275 keV lines). *Bottom right:* multiple-site events, ^{22}Na , same experiment. The line at 1465 keV (^{40}K) is due to natural radioactivity of the ceramic (MACOR, which contains about 10% potassium) used around the wire structure and field shaping rings.

limited DAQ. The light-trigger efficiency was measured for energies up to 2 MeV spatially resolved with fine granularity. From these data, a detailed model of the detector trigger efficiency was derived.

Another handle we have to select multiple-site events is to reject single-site events on-line. This selection, based on the number of wire hits, is implemented in the LXeGRIT data acquisition software. This selection is very powerful, with very low acceptance of single-site events at energies below 2 MeV and about 50 % above 5 MeV, where the fraction of single-site events is anyway small * .

2.2. In-flight Performance

A primary goal of the LXeGRIT balloon experiment was to measure the background rate at float altitude for this novel instrument. Since the maiden engineering flights from Palestine, TX, in the Summer of 1997, LXeGRIT has been improved and has successfully flown again twice from Ft. Sumner, NM, in May 1999 and in October 2000. The improvements were focused on the DAQ and trigger system, onboard data storage and telemetry, as well as on instrument support systems^{?, ?, ?}.

*More details about the LXeGRIT efficiency in flight 2000 configuration are given in Curioni et al. "On the Background Rate in the LXeGRIT Instrument during the 2000 Balloon Flight"[?]

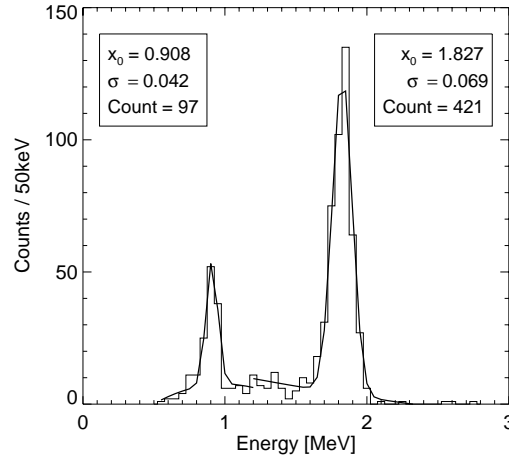


Figure 4. ^{88}Y “3-site events” energy spectrum, after event selections and CSR

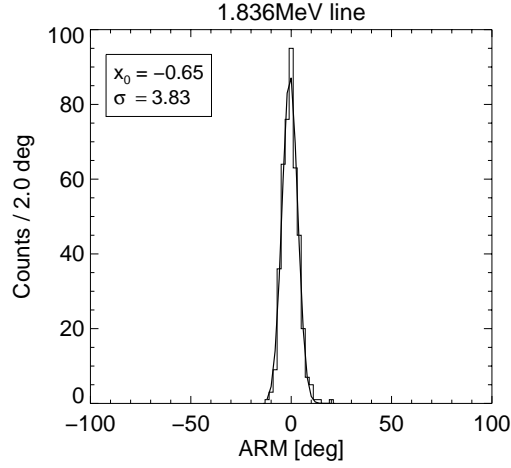


Figure 5. Measured angular resolution distribution for 1.8 MeV

The TPC itself was never modified and has required only minimal repairs during the five years since 1997. The 1999 flight lasted almost 10 hours, while the 2000 flight lasted 27 hours, including two hours ascent, with 40 GB of data collected. It was launched on October 4 from the National Scientific Balloon Facility in Fort Sumner, New Mexico, at 19:39:48 UT and the detector operation was stable throughout the flight. The electronics, cryogenics system and DAQ performed as expected from testing in the laboratory. Some relevant parameters describing the flight conditions are summarized in Fig. 7. The payload was recovered in good conditions 10 miles south of Buckeye, Arizona.

A detailed description of LXeGRIT in the 1999 flight configuration is given in Aprile et al.[?], which can be considered as a reference also for the 2000 flight configuration but for three relevant points:

1. the active NaI(Tl) and liquid scintillator shields, surrounding the LXeTPC, were removed to better understand the response of the TPC itself to space radiation. The plastic scintillator charge particle shield above the TPC was also removed;
2. a gain of a factor 2.5 in DAQ speed (see Aprile et al.[?]) and a factor of about 2 in inflight event data transfer to ground;
3. optimization of the light trigger and on-line selections for MeV multiple-site events (see Oberlack et al.[?] and Curi-
oni et al., accompanying paper in this proceeding).

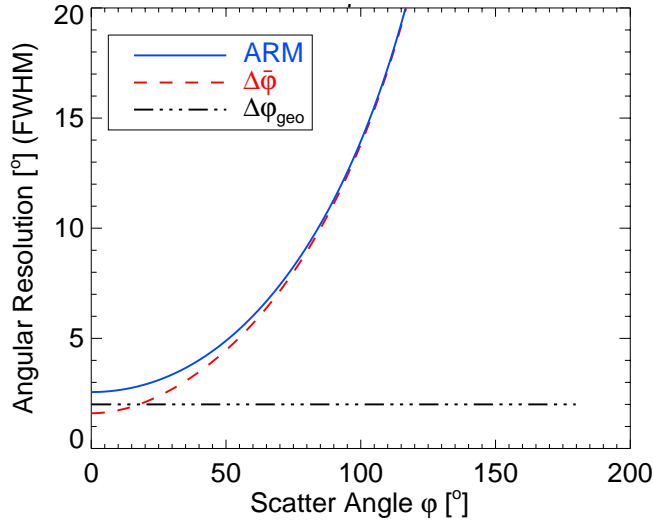


Figure 6. Expected angular resolution vs. $\bar{\phi}$ for 1.8 MeV photons (solid line) and contributions from energy resolution (dashed line) and position resolution (dash-dotted line).

The energy spectrum of single- and multiple-site events recorded at balloon altitude in the period 12:00 - 17:00 UT is shown in Fig. 8. As discussed in Curioni et al. in this proceeding, the measured spectrum is reproduced within a factor of 2 with atmospheric and cosmic diffuse γ -ray fluxes, a mass model of the payload, and a model of the internal background as measured on the ground, suggesting that activation of passive materials due to atmospheric neutrons and protons is only a small contributor in this unshielded detector. The instrument has been modeled using the GEANT package and all the required instrument parameters (energy thresholds and resolution, spatial resolution, light-trigger efficiency etc.) have been measured independently, while the livetime fraction of the DAQ system is computed on-line.

The 1.46 MeV line, clearly visible in the multiple-site events of Fig. 8, is attributed to natural ^{40}K radioactivity, mostly from the machinable ceramic (MACOR), used to support the TPC wire structure and the field shaping rings. Macor contains about 10 % potassium oxide. The ^{40}K line and most of the continuum below 500 keV, is present at a similar rate in the LXeGRIT background spectrum measured on the ground. Activation of the xenon itself also appears negligible, as we do not detect any other line. This observation is consistent with laboratory experiments with LXe detectors exposed to neutron beams and experiments in deep space (see Kirsanov et al.[?] and Ulin et al.[?]).

As reported previously[?], the number of multiple-site events recorded during the 1999 balloon flight was largely reduced compared to single-site events. The light trigger threshold was set very low; the thick NaI shields below and around the TPC were supposed to veto a large fraction of this component. Once afloat, the trigger rate turned out unexpectedly large and the trigger upper discriminator threshold was lowered to reduce the DAQ dead-time, cutting into the MeV band. Analysis of the data and Monte Carlo simulations with atmospheric neutron flux indicate that a combination of neutron induced background from shields activation, only partially working shield sections, and the enhanced trigger efficiency at low energy, may explain the measured background rate and spectral shape.

For the 2000 flight we removed all the shields and optimized the detection efficiency for multiple-Compton events in the few MeV energy region. The trigger rate as given by the PMT-OR was relatively low, ~ 600 Hz and nearly constant throughout the flight, after ascent had been completed. Albeit the PMT-OR gave a much lower rate compared to the one during the 1999 flight, the final rate of MeV γ -ray events after selections is much higher for the 2000 flight settings. A comparison between the two flights is shown in Fig. 9 where the rate is normalized to the total exposure, but not corrected for DAQ livetime. The much improved efficiency in the MeV region and the increased number of multiple-site events in the 2000 flight data is self-evident.

Beyond establishing the in-flight background spectrum in an LXe Compton telescope, we would like to prove its imaging performance and background suppression capability by identifying the signal from the Crab nebula. We have in fact seen hints for a signal of the proper strength in two independent data samples, based on 2-site and 3-site events. ARM

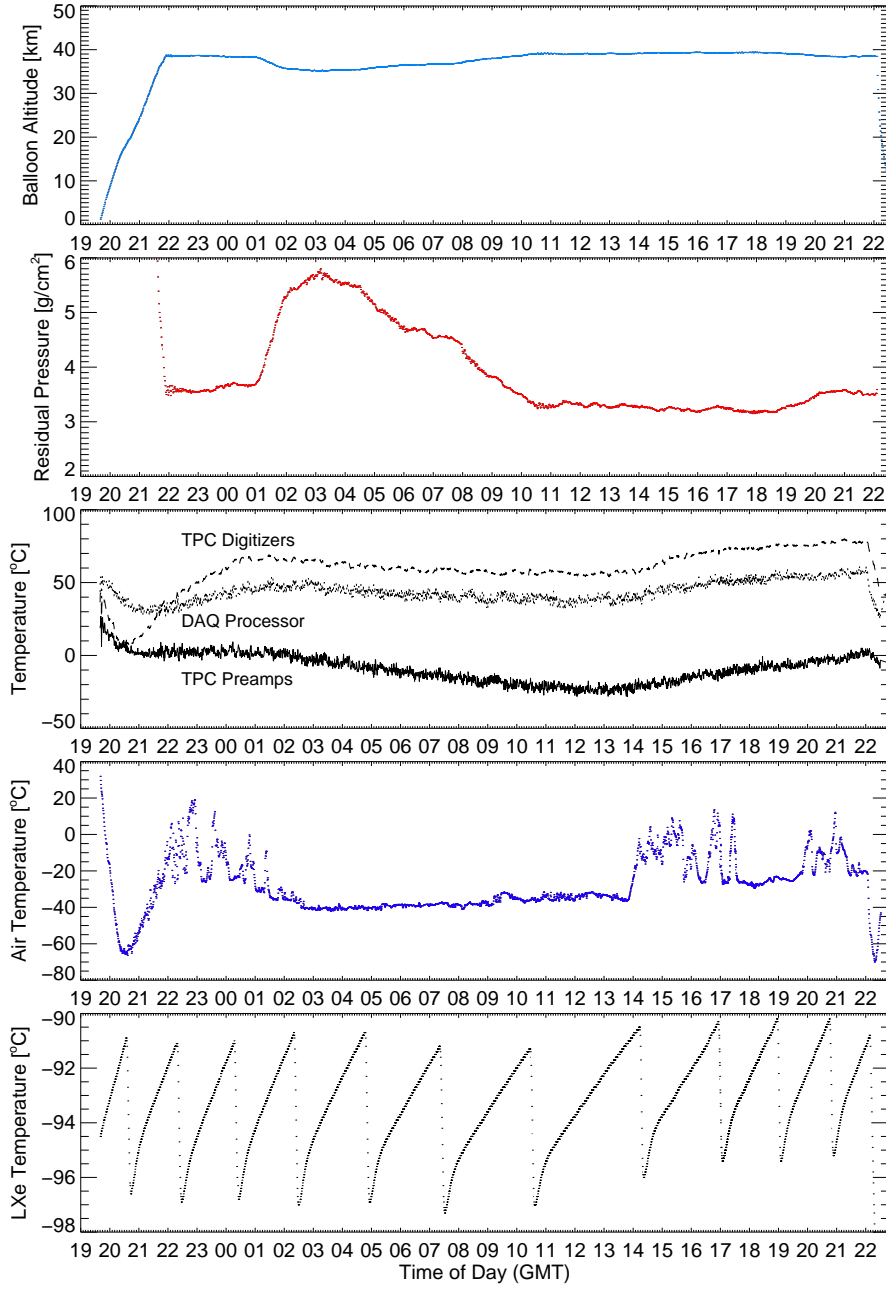


Figure 7. *From top to bottom:* 1. balloon altitude during flight; 2. corresponding atmospheric depth; 3. temperatures as measured by sensors placed at three different locations (TPC preamplifier boxes, DAQ processor and TPC electronics board); 4. air temperature - some apparently wild variations are due to direct exposure to the Sun as the gondola rotates around its vertical axis; 5. liquid xenon temperature - the “dips” correspond to cooling cycles with liquid nitrogen.

spectra show an excess at $\text{ARM} = 0^\circ$, which is not present in background spectra. We are still studying the impact of event selections on signal/background during the flight. Our current efforts are pointed towards identifying the data cuts that best reject background without further reducing the limited number of source counts. This includes careful studies of the events we have rejected in a first analysis based on event quality, a study of fiducial volume and spatial separation cuts, optimized also with the help of Monte Carlo simulations, and improving the algorithms to identify the proper interaction sequence. We are also working to improve background models for a likelihood imaging analysis, and we plan to search for timing

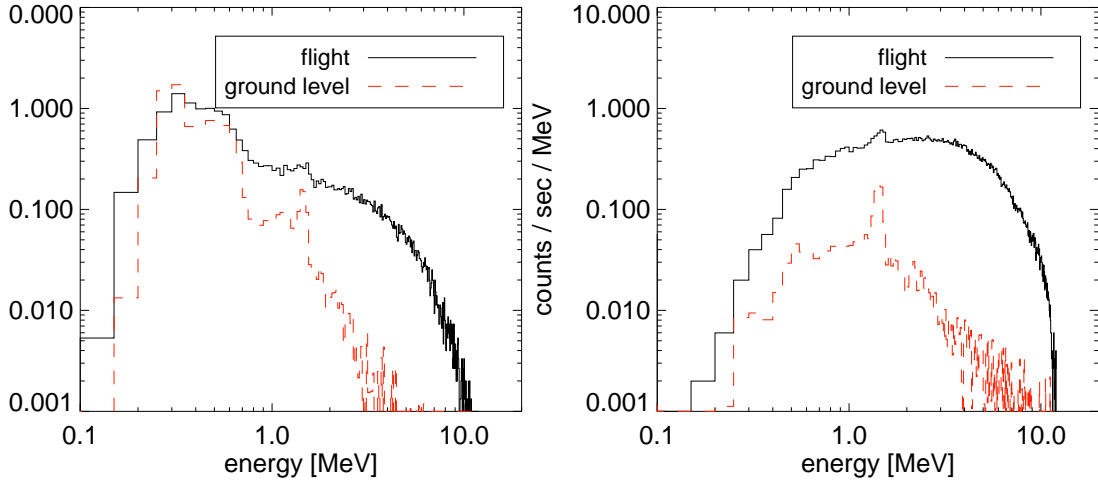


Figure 8. Energy spectra for flight data (*continuous line*) and for a background run at the ground level (*dashed line*). *Left*: single site events. *Right*: multiple interaction events.

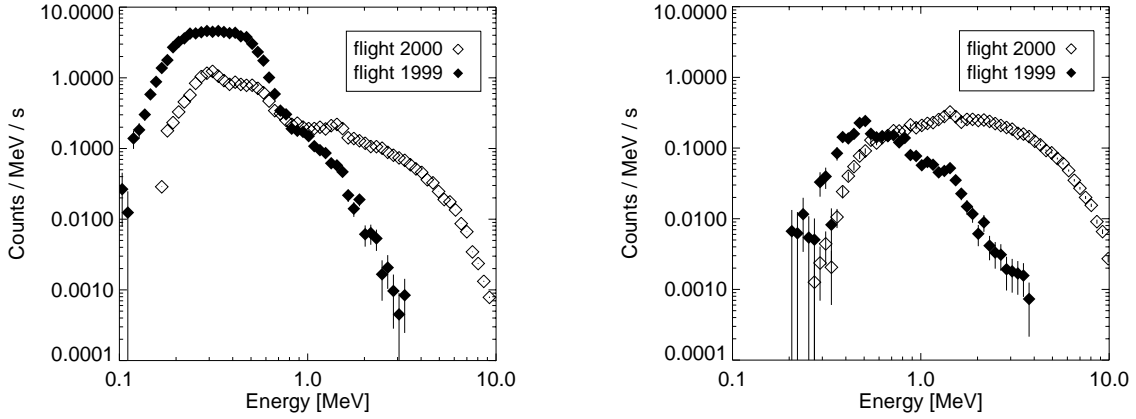


Figure 9. In-flight energy spectra, normalized to the total exposure but not corrected for DAQ livetime: 1999 and 2000. *Left*: single-site events, *right*: multiple-site events.

structure in our data from the Crab pulsar. The results of this ongoing effort are beyond the scope of this paper and will be reported elsewhere.

3. FUTURE PROSPECTS: LXEGRIT-2 AND BEYOND

Following the 2000 flight, several experiments with the TPC have been carried out for post-flight calibration and for studies of the light trigger system. From the extensive set of measurements, data analysis results, and simulations, we have identified strengths and weaknesses of the current prototype design. While various goals of basic research and development remain to explore the full potential of this technology, we consider the LXeTPC technology mature enough to allow implementation of a large instrument in the near future. We will summarize in the following two sets of improvements that would vastly boost the efficiency and overall performance of the current instrument. The first set, described in Sec. 3.1, could be implemented as a very significant upgrade of the current system, which we call LXeGRIT-2. The second set would go even further, towards the development of a base module for a next-generation Compton telescope based on LXeTPC technology.

3.1. LXeGRIT-2

The following measures have been identified for upgrading the current detector, largely maintaining the current read-out system. We have started to implement a new light trigger system and the other changes have been studied.

1. Install a new light detection system based on 12 Hamamatsu R6041 phototubes in the liquid surrounding the sensitive volume from all sides. The sum signal of the 12 PMTs, followed by the window discriminators already available, will provide the TPC trigger.
2. Replace the cathode and HV connections to operate the TPC at 3 kV/cm electric field. Move the front-end amplifiers inside the cryostat in close proximity to the signal feedthroughs. Minimize analog pre-filtering before digitization on the anodes.
3. Add two more readout processors in order to read the X- wires, the Y- wires, and the anodes in parallel.
4. Add a plastic scintillator shield to veto charged particles at the trigger level.
5. Add a Global Positioning System (GPS) interface for precise event time stamping, needed for pulsar studies.

The first modification is to enhance the energy sensitivity of the trigger and thus reject background outside the energy band of interest without requiring action of the readout processor. The current geometry, with four external PMTs, gives a poor light collection efficiency and a large, position dependent, amplitude spread. This requires a very low trigger threshold. Our raw trigger rate is then much higher due to low energy background and noise pulses. The new geometry, with 12 PMTs surrounding the TPC sensitive volume, and the addition of UV reflectors, would give about tenfold increase in light collection, as shown by ray-tracing simulations. The ability to detect the γ -ray source energy with the light will allow to select the energy band of interest at the trigger level. At 1 MeV, an increase in trigger efficiency from $\sim 10\%$ to $\sim 100\%$ is expected. A direct consequence of the better light collection efficiency is to improve the energy resolution by adding the scintillation signal to the ionization signal. This is currently being investigated with a small ionization chamber equipped with one Hamamatsu R6041.

The Hamamatsu R6041 PMT is a 2" diameter, metal channel tube. It was a special development for LXe detectors. We have tested its performance in LXe and studied its compatibility with the high purity requirement for drifting charges. Machining of the Teflon (90% reflectivity in the UV) walls supporting the PMTs is complete and a new design of anode and cathode to increase reflectivity is underway. The new geometry will also eliminate triggers from the layers of LXe outside the fiducial volume. In the present chamber, with the PMT's viewing the chamber from below, a 3 cm LXe layer below the anodes is an efficient scintillator slab, in which background events easily produce false triggers.

The second modification will bring both better energy resolution and lower electronic noise, and thus lower energy thresholds. The drift field on the TPC is currently limited to 1 kV/cm. By replacing the cathode and the HV connections, we will be able to increase the applied voltage from 9 kV to 25 kV, needed for a 3 kV/cm drift field. For this increase in applied electric field, we have previously measured the FWHM energy resolution to improve from 12.5 % to 7.5 % for 662 keV (^{137}Cs).

With a clever arrangement of the 128 signal feedthroughs on a new TPC bottom flange, we will be able to connect the charge sensitive amplifiers with minimum stray capacitance, and thus reduce the noise. For the anodes the capacitance will be reduced from the current 76 pF to 24 pF, corresponding to a reduction in the noise level from 1200 electrons RMS to about 480 electrons RMS.

With lower noise, analog pre-filtering before digitization, and therefore signal shaping, can be significantly reduced, minimizing the separability of two signals on the same anode from the current value of ~ 4 mm. This would further improve the number of optimally reconstructable events, for which wire and anode signals are fully matched.

The third action of increasing the number of readout processors will bring an additional increase in overall efficiency. As previously mentioned, the current DAQ system is about 50% dead-time limited for a trigger rate of few hundreds Hz, because of the slow data transfer from the digitizers. Since the on-line software treats the X-wire, the Y-wire and the anode signals nearly independently, the time required to process an event is reduced by a factor 2.5 by splitting the tasks and having three processors work in parallel. All three processors will run the same software as in the present readout, but each

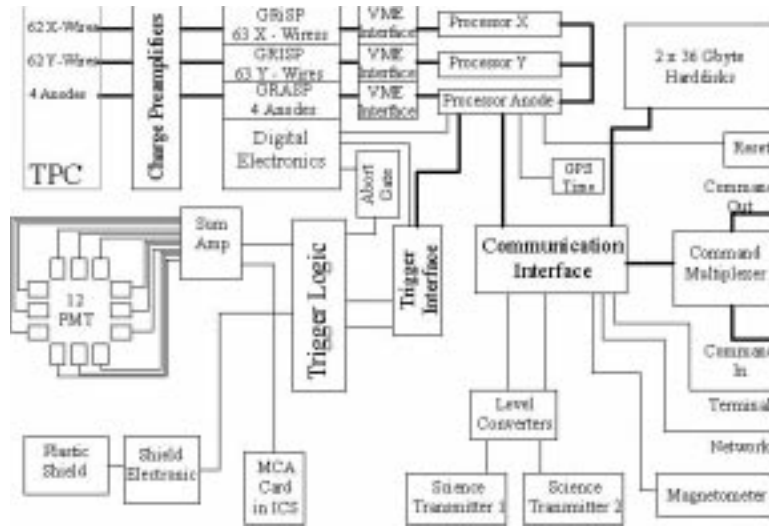


Figure 10. Block diagram of the LXeGRIT-2 flight system.

is connected to only one section of the digitizer system. Once accepted, the data will be combined to form a single event and sent either to the telemetry transmitters or the two hard disks for onboard storage.

Finally, with a plastic shield fully covering the TPC, charged particles will be vetoed at the trigger level. As we have directly verified, the majority of charged particles can be easily identified from the large energy detected on the anodes and rejected by the on-line DAQ software. Particles cutting the corners deposit much less energy and require more off-line processing to ensure they are not confused with γ -ray interactions at the edge of the detector. In the current system, a charged-particle rejection on the trigger level could reduce the event rate to be handled by the DAQ system by as much as 2/3. In 1999, a thin plastic counter was used to cover the TPC aperture, since the sides and bottom were covered by the UNH NaI shields. In 2000, all shields were removed. The charged particle rate measured from the in-flight data digitized in full mode, was about 400 Hz, more than 60% of the total trigger rate of ~ 600 Hz. The proposed shield for the next LXeGRIT flight will keep processing time low by vetoing all charged particles in the trigger. Together with the energy sensitivity of the light trigger, we expect to entirely defeat the present dead-time limited behavior of the DAQ system, and effectively increase the amount of science data by a factor two for the same flight time (Fig. 10).

A commercial GPS together with a time interpolator would provide microsecond timing accuracy. Currently, LXeGRIT events have a time stamp derived from the microprocessor clock. This clock, however, does not have the required stability and precision for pulsar timing analysis.

The combination of upgrades is expected to increase the detection efficiency for multiple-site imaging events in the 1-3 MeV band to the 3.5% level, as originally simulated for the LXeTPC. With 14 cm^2 effective area and the background level measured in the last flight, reduced by about 15% through Compton imaging, we expect ~ 730 source counts from the Crab and ~ 1900 background counts in the 1-3 MeV band. This corresponds to a 3σ sensitivity of $3.7 \times 10^{-4} \text{ ph/cm}^2/\text{s}$, for a $3 \times 10^4 \text{ s}$ balloon observation, or a 14σ Crab detection. With the improved LXeGRIT we will be able to look for polarization in the Crab Nebula and pulsed spectra at MeV energies, and could make sensitive observations of other sources such as Cyg X-1, 3C273, GRS1915+105 and the Orion Nebula.

3.2. Towards a Next-Generation LXe-Based Compton Telescope

The overall efficiency of a next generation Compton telescope based on an array of independent LXeTPCs could be maximized along the following lines:

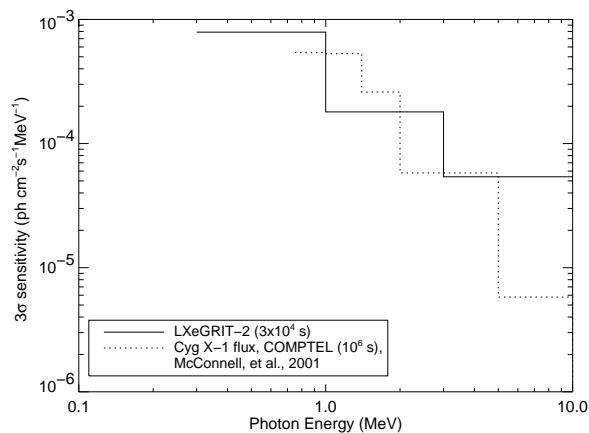


Figure 11. LXeGRIT-2 continuum sensitivity

1. Use thicker LXeTPC modules, with two or more drift regions for improved photopeak efficiency and optimal electric field strength. Maximize the information from the scintillation light, to effectively use this channel not just for triggering, but for improved energy measurement and for background rejection based on pulse shape discrimination.
2. Develop a new DAQ system with fast DSP's to perform full online event reconstruction and minimize the event rate to be transmitted to ground.
3. Develop a charge readout with improved spatial resolution, replacing the current set of anodes, wires, and wire mesh. This would reduce the current requirements for matching X- and Y-wire signals as well as wire/anode signals, which lead to significant event losses in the current design.

This is a just short list of some improvements that would require more extensive studies and development and are more suitable for a new detector module rather than an upgrade of the current LXeGRIT.

Conclusions

In this paper we have presented various laboratory and in-flight performance results achieved in the period 1999 – 2002 by the LXeGRIT collaboration. These results show that the instrument is a fully tested, fully operational balloon borne Compton telescope. The experience with the LXeGRIT prototype has also been valuable to identify weaknesses of the current TPC design and signal readout, for which we have presented solutions for an upgraded detector or a future new detector module. LXeGRIT had a successful 27 hour balloon flight in the year 2000 and the continuing analysis of the 40 GB of data collected at balloon altitude is giving us a complete understanding of the performance expected from the instrument. The measured γ -ray background in LXeGRIT at float altitude is in good agreement with that expected from the known atmospheric and cosmic diffuse components without having to invoke large contributions due to activation of Xe by atmospheric neutrons or spallation-induced backgrounds in passive materials at balloon altitude. Analysis improvements are currently underway, and we are working at publishing a more in-depth report on the efficiency and in-flight sensitivity of LXeGRIT in its 2000 configuration. We are now planning to increase the sensitivity to astrophysical interesting γ -ray sources. A new balloon flight with such improved detector would validate this performance and help achieve the full science potential of LXeGRIT. Further studies are required for a next-generation LXe-based telescope.

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Expected Angular Resolution for LXeGRIT

Energy Resolution D1 - D2: 10.0% - 10.0% * $\sqrt{E/1\text{MeV}}$, Position Resolution 2.0° (FWHM)

